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DESIGN OF MICROWAVE WAVEGUIDE SENSOR WITH ARTIFICIAL STRUCTURE FOR DIELECTRIC PROPERTIES OF MATERIAL INVESTIGATION

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Abstract

In the paper we describe a new approach to the dielectric properties of dielectric material investigation with implementation of artificial metamaterial structure over the aperture of waveguide sensor in order to increase the sensing properties of classical waveguide sensor and to achieve the optimal design of metamaterial structure for waveguide sensor tuning in microwave X-band. In the paper the possibility to investigate metamaterial structure using for upgrading properties of classical waveguide sensor is studied, the numerical simulation of 2D metamaterial structure properties and experimental results for dielectric properties dielectric materials are carried out.

Keywords: *complex permittivity; waveguide; microwave frequencies; X-band; metamaterial structure*

Introduction

Microwave waveguide sensors can measure properties of materials based on microwave interaction with matter, and they can be used to provide information about dielectric properties of investigated dielectric material characterized with complex permittivity, and with that knowledge can afford information about moisture content, density, structure, and even chemical reaction. Microwave sensor offers many advantages in comparison with traditional sensor such as rapid and nondestructive measurement [1]. At microwave frequencies, dielectric properties of materials depend on frequency, moisture content, bulk density and temperature.

Metamaterials are defined as effectively homogeneous artificial electromagnetic structure which exhibits unusual electromagnetic properties especially the backward wave and negative refraction, which cannot be find in nature. One of the most important features of the metamaterials is the enhancement of the evanescence field [1], which has been used to enhance the near field sensors. The resonant properties of metamaterials results in frequency dispersion and operation in narrow bandwidth and the center frequency is fixed by the geometry and dimensions of the elements comprising the metamaterial composite.

Among various applications, the metamaterials can be used to improve sensing of classical microwave devices in such way metamaterials open a new degrees of freedom in sensor design like a sensitivity increasing [2].

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Metamaterial Unit Design

The aim is to design a sensor able to complex permittivity change in the way of classical waveguide tuning with metamaterial structure. As a metamaterial structure, one metamaterial unit (MMU) has been proposed. Individual components MMUs respond resonantly to the electric, magnetic or both components of the electromagnetic field. In this way, electromagnetic metamaterials can be designed to obtain a required response at frequencies from the microwave to the near visible [3]. Since the interest was to investigate the dielectric properties in microwave X band, metamaterial structure for this frequency band have been designed. MMU designs of interrupted rectangular structure is shown in Fig. 1 (a) and interrupted double rectangular structure is shown in Fig. 1 (b) [4] The response of MMU to the applied electromagnetic field is possible affected by the change of MMU dimensions. Another way to change the magnetic response of MMU is to add another unit or to add another interruption to its shape.

In this new approach the metamaterials function in two ways: like a tool for increasing the sensibility of classical waveguide sensor and the tool sensitive to the dielectric properties of investigated material through the adjusted resonance frequency of designed MMUs.

a b

Fig. 1. Design of metamaterial unit for (**a**) single MMU and (**b**) double MMU.

The MMU was realized on the highfrequency substrate Roger RT/Duroid 5870 with the thickness of 0.508 mm, which due its low dispersion is appropriate for applications in GHz frequency range. The relative permittivity of used substrate is $\varepsilon_r = 2.33$ and loss tangent $\tan\delta = 0.0012$ and both parameters are constant in the working frequency band of MMU.

The dimensions of MMUs were designed and optimized by using commercial software CST Microwave Studio. The resonant frequency of MMU was tuned up by changing its inductance and capacitance by adjusting width of metamaterial rectangle (see Figure 1, dimension *a*) and by the width of rectangle interruption (see Figure 1, dimension *c*); or to change the distance between inner and outer rectangle of MMU (see Figure 1, dimension *b*).

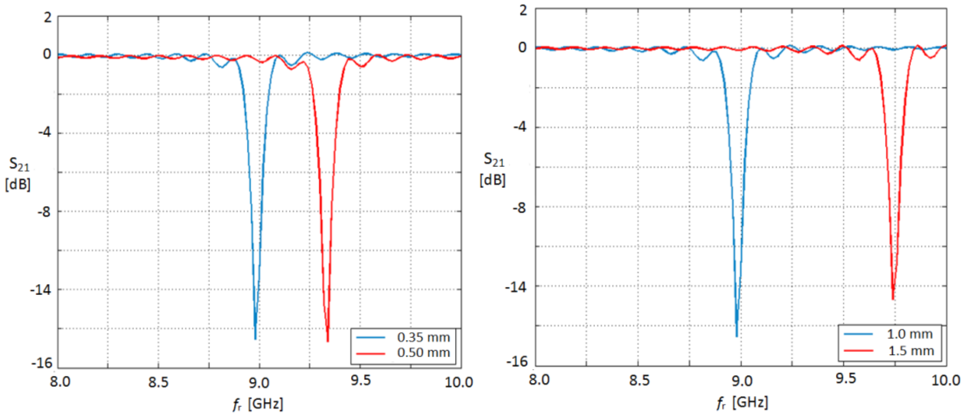
The Influence of Rectangle Interruption Width on Resonant Frequency of single MMU

The interruption of MMU (Fig. 1, dimension *c*) functions like the plate capacitor. If the distance between plates of capacitor *d* is increasing, the capacity of capacitor and then the capacity of MMU are decreasing, causing the increasing the MMU’s resonance frequency.

The influence of MMU interruption on resonance frequency shift in the case of single MMU is in Fig. 2 (a). The interaction of proposed MMU with electromagnetic field is studied by frequency dependence of scattering parameters S_{11} (reflection coefficient) and S_{21} (transmission coefficient). The influence of MMU interruption on resonance frequency shift in the case of single MMU is shown in Fig. 2 (a). The resonant frequency increasing with the increasing of rectangle interruption width is in good accordance with theory.

The Influence of Metamaterial Rectangle Width on Resonant Frequency of single MMU

In the case of increasing the width of metamaterial rectangle (see Fig. 1, dimension *b*), it can be shown in Fig. 2 (b) that not only resonant frequency is shifted, but also the transmitted signal is more damped in comparison with the signal transmitted through MMU with thinner shape.

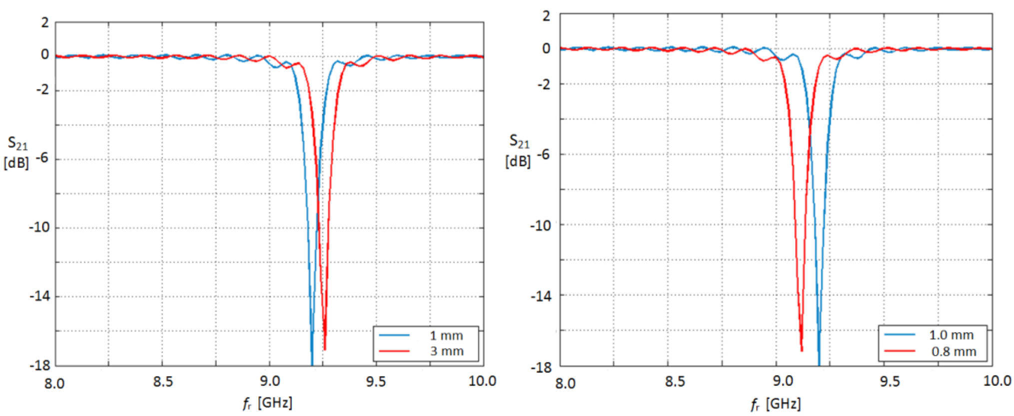


a b

Fig 2. Design of MMU; resonant frequency as a function of width (dimension *c* and dimension *b*) transmission coefficient S_{21} as a function of frequency.

The Influence of Rectangle Units Distance on Resonant Frequency of Double MMU

In the case of increasing of outer dimensions of inner structure up to analytical model of Sauivac [5] the width of rectangle influences all capacities and inductances, including mutual in MMU structure. The increasing of width of rectangle causes decreasing of mutual inductance and mutual capacity both inner, and outer rectangles. It means, that with the narrow width of rectangle is connected lower resonance frequency, and vice versa with broad higher value of MMU resonant frequency. The dimensions of MMU were stated up to results of numerical simulation in Fig. 3.



a b

Fig. 3. Design of metamaterial unit; resonant frequency as a function of a) structures distance for double MMU, b) width of rectangle of MMU; transmission coefficient S_{21} as a function of resonant frequency.

Waveguide sensor Tuned with Metamaterial Structure

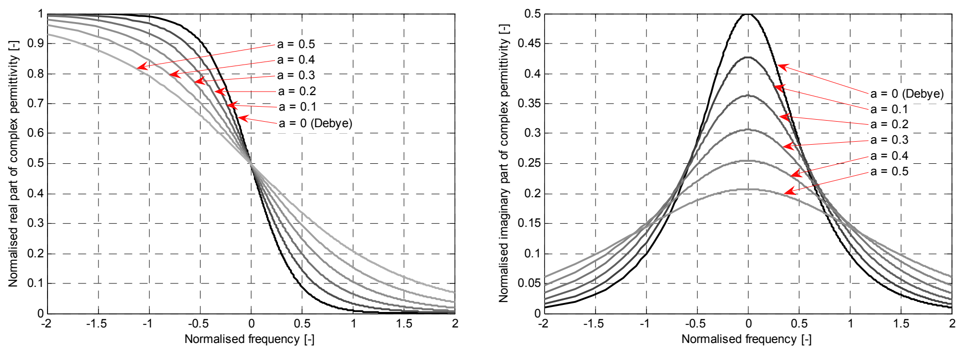
The aim was to design sensor able to complex permittivity change. This fact can be observed via changes of distribution parameter *α* in Cole - Cole equation:

$$\dot{\varepsilon}_{\mathrm{r}} = \varepsilon_{\infty} + \frac{\varepsilon_{\mathrm{s}} - \varepsilon_{\infty}}{1 + \left(\mathrm{j}\omega\tau\right)^{1-\alpha}} \tag{1}$$

where ε_{s} and ε_{∞}, are static and infinite permittivity, respectively, ω is angular frequency, τ is the mean relaxation time for dielectric and distribution parameter, α is a constant for dielectric, $0 \leq \alpha \leq 1$.

The distribution parameter characterizes the width of relaxation spectra of investigated dielectric material [6, 7]. The explanations of complex permittivity given in eq. (1), which represents polarizing effects in dielectrics, do not consider the temperature changes [6, 7].

The changes of distribution parameter *α* is induced by the changes of investigated material permittivity. The simulation results for frequency dependence of real and imaginary part of material complex permittivity for various values of distribution parameter *α* are presented in Fig. 4. The declination of curve in Fig. 4 (a) is changing with variation of *α* and with the variation of width of frequency band, which is connected with values of real and imaginary part of complex permittivity (see Fig. 4 (b)).

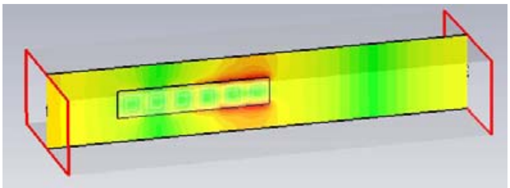


a b

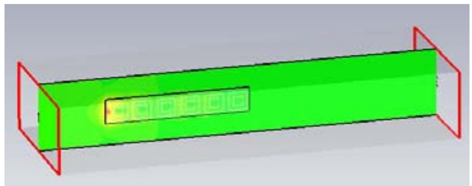
Fig. 4. The frequency dependence of (**a**) real and (**b**) imaginary part of complex permittivity for various values of distribution parameter α in Cole – Cole equation.

The proposed waveguide sensor with metamaterial structure induces the band-stop properties of the sensor. The metamaterial structure (MMS) can be designed for chosen frequency band to be able to the changing value of investigated dielectric material complex permittivity. In the case of dielectric characteristic of investigated material changing, the sensor starts work with another value of distribution parameter and will change the frequency band to which the sensor senses. The frequency spectrum of reflected signal from the investigated dielectric can be determined and its changes respond to dielectric properties of tested material.

The numerical results for transmission of microwave signal in new waveguide sensor tuned with MMS are shown in Fig. 5. The situation of state which responds to the dielectric properties of investigated material is presented in Fig. 5 (a). When dielectric properties of investigated material are changed, the sensor become insensitive and microwave signal is not transmitted, Fig. 5 (b), where is displayed situation of changed dielectric properties. It can be seen, that the waveguide sensor is frequency selective and can be able to the changes of material dielectric properties.



a



b

Fig. 5. The electromagnetic field distribution in waveguide sensor with metamaterial structure at (**a**) nonzero and (**b**) zero transmission.

The Bandstop Width of MMU Adjustment

The MMU would yield a negative value of permeability and the wire structure a negative value of permittivity. The resonant behaviour and band-stop properties of MMS were numerically simulated and experimentally observed by measuring the transmission through the waveguide with inserted MMS. The proposed MMU (see Fig. 1(b)) interaction with electromagnetic field is studied by frequency dependence of scattering parameters S_{11} a S_{21}. Fig. 6 shows the band-stop properties of one MMU.

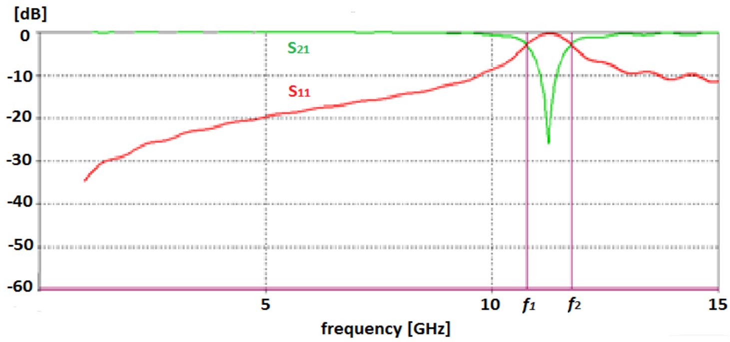


Fig. 6. The S_{11} and S_{21} – parameters of band-stop filter characteristics for one metamaterial unit.

The number of MMUs was optimised for band-stop (the bandwidth Δf = 1.85 GHz, low frequency f_1 = 10.48 GHz, high frequency f_2 = 12.33 GHz) with numerical simulation of *S* parameters (Fig. 7).

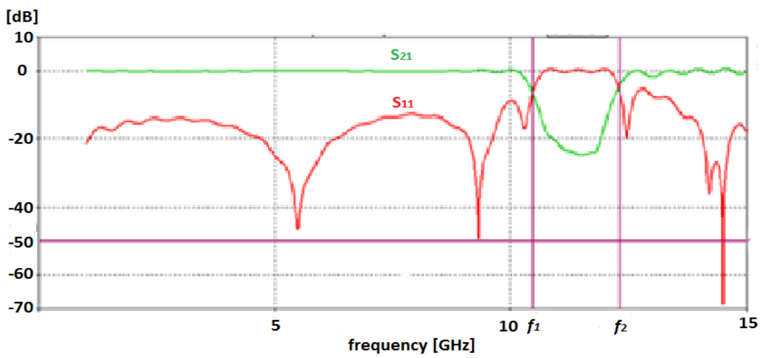


Fig. 7. The S_{11} and S_{21} – parameters of band-stop filter characteristics for designed waveguide sensor.

The optimal number of MMUs on substrate for chosen frequency band-stop is 6; optimal number of substrates with MMS inserted to the volume of waveguide is 3. The dependence of band-stop width on number of MMUs (SRR) is presented in Fig. 8.

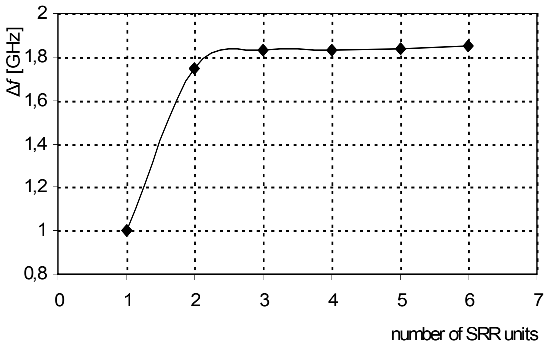


Fig. 8. The optimization of waveguide sensor tuned with band-stop filter.

Results

The measurements of sample dielectric properties were performed with Vector Network Analyzer (VNA) and scattering parameters were measured in the X frequency band. Identical structures of MMU located in the volume of waveguide sensor were used at measurement. Few dielectric samples were measured and the shift of resonant frequency for each measurement was obtained. To acquire results for permittivity, the calibration curves for one to four MMUs placed in the front of classical waveguide sensor were numerically determined.

From calibration curves, it is possible to acquire the value of relative permittivity by inverse procedure. That means if the resonant response of MMU is known, the value of permittivity for investigated sample can be found by using calibration curve for one to four MMU.

The calibration curves for different number of identical MMU placed in the volume of waveguide sensor are presented in Fig 9.

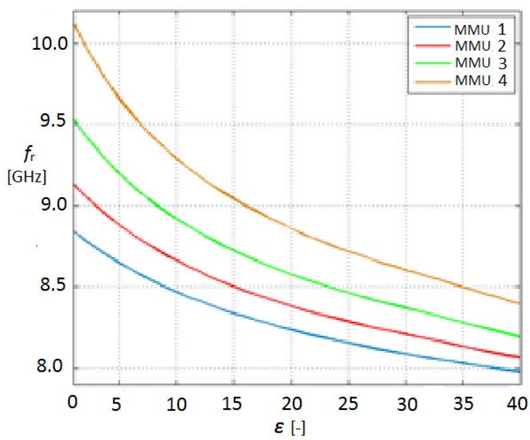


Fig. 9. Calibration curves for dielectric constant calculation.

Comparing the measurement with MMU with the classical measurement without using of MMU, the results are presented in Fig. 10. For both measurements – with and without MMU – the same samples with known value of permittivity were used. According to literature, it can be shown that the measurement with MMU placed in the volume of classical waveguide sensor has high accuracy.

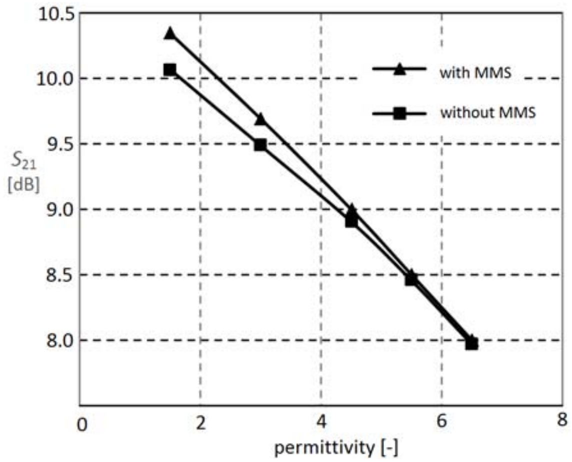


Fig. 10. Comparison of permittivity measurement with and without MMS inserted to the volume of classical waveguide sensor.

From Figure 10 it can be also seen that the accuracy of sensor is decreasing with the increasing of sample permittivity and for samples with permittivity higher than six the results for both measurement with and without MMU are closed. The sensor tuned with MMSs is appropriate for the dielectric material with low value of dielectric constant.

Conclusions

The numerical and experimental results showed that waveguide sensor tuned with metamaterial unit is more precise at the permittivity estimation in comparison with classical open waveguide sensor, because the evanescent wave is amplified by using metamaterial unit. The metamaterial unit can be numerically designed for requested resonant frequency up to character of investigated dielectric sample - low or high loss dielectric materials. The sensor tuned with designed metamaterial structure has also the frequency selective properties. The resonant response of sample can be evaluated by measurement of scattering parameters. The designed waveguide sensor tuned with metamaterial unit can be used not only for permittivity of dielectric sample measurement but also for monitoring of sample permittivity changes.

Acknowledgments

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